SEM Performance Evaluation using the Sharpness Criterion[1,2]

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ABSTRACT

Fully automated or semi-automated scanning electron microscopes (SEM) are now commonly used in semiconductor production and other forms of manufacturing. The industry requires that an automated instrument must be routinely capable of 5 nm resolution (or better) at 1.0 kV accelerating voltage for the measurement of nominal 0.25-0.35 micrometer semiconductor critical dimensions. Testing and proving that the instrument is performing at this level on a day-by-day basis is an industry need and concern and is addressed in this paper. Furthermore, with the introduction of fully automated inspection and metrology instrumentation, not only does an appropriate, easy to obtain or manufacture measurement sample have to exist, but also an objective and automated algorithm developed for its analysis. Both of these have been the objects of a study at NIST and the fundamentals are discussed in this paper. In scanning electron microscopy, two of the most important instrument parameters are the size and shape of the primary electron beam and any image taken in a scanning electron microscope is the result of the sample and electron probe interaction. The low frequency changes in the video signal, collected from the sample, contains information about the larger features and the high frequency ones carry information of finer details. In principle, if the sample geometry is known, the geometric parameters of the primary electron beam are mathematically determinable from an acquired image. The method described in this paper is based on the frequency domain representation of a scanning electron microscope image and can also be used to check and optimize two basic parameters of the primary electron beam, the focus and the astigmatism. The application of this technique to regularly check the resolution of the SEM in quantitative form will also be discussed.

Keywords: scanning electron microscope, SEM, standard, sharpness, resolution, performance, beam diameter

2. INTRODUCTION

Today, scanning electron microscopes (SEM) are used in many manufacturing environments. Fully automated or semi-automated scanning electron microscopes are now commonly used in semiconductor production and other forms of manufacturing. The industry requires that an automated instrument must be routinely capable of 5 nm resolution (or better) at 1.0 kV accelerating voltage for the measurement of nominal 0.25-0.35 micrometer semiconductor lines. Testing and proving that the instrument is performing at this level on a day-by-day basis is an industry need and concern which NIST is attempting to address. No good wafer level performance standard currently exists to assist in this task. The NIST SEM performance standard SRM 2069[5]

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is not useful for production-type of instrumentation and samples such coated latex spheres can introduce both the possibility of particle and noble metal contamination. Furthermore, with the introduction of fully automated inspection and metrology instrumentation, not only does an appropriate sample have to exist but also an objective and automated algorithm must be developed for analysis. Both of these needs have been the objects of a study at NIST and the fundamentals are discussed in this paper.

The spatial resolution of the secondary electron image is one of the comparative factors used in the determination of the performance of scanning electron microscopes. Overall, the potential resolution of the SEM has improved by one order of magnitude over the past decade[10] and many of the reasons for these incremental improvements in performance have been previously discussed.[15] Concern over instrument resolution and its limits have always interested researchers and a number of studies exist regarding this topic which theoretically and practically investigate its measurement.[6,7,13,18,19]

2.1 SEM Performance.

There are three major factors that can be considered when attempting to determine the performance of an SEM. These factors are: beam diameter measurement, resolution measurement and sharpness measurement.

2.1.1 Beam Diameter Measurement. Studies of the methods of measurement of electron beam diameter have been made and clearly the knowledge of the diameter is valuable especially where electron beam lithography and electron beam metrology are concerned. For accurate metrology to be achieved in the SEM, a measurement of the electron beam diameter is imperative. The electron beam diameter is an input parameter for the electron beam modeling.[11,12] Since resolution and probe size are directly interrelated, attempts have been made to develop techniques for the measurement of accessible instrument parameters (such as beam diameter) and to extrapolate this measurement into a means of determining the potential resolution of the electron microscope.

2.1.2 Resolution Measurement. The measurement of the resolution of an SEM is an important function especially where the acceptance of an instrument is concerned. Depending upon the type of instrument, there are different expected performance levels.[15] Most SEM manufacturers provide comparative specifications for the expected performance of the instrument. Measurement of the resolution is typically **a subjective** procedure generally done from a micrograph using special samples constructed for the specific purpose of proving resolution.

2.1.3 Sharpness Measurement. The sharpness concept is a more practical approach to the issue of the evaluation of instrument resolution. The sharpness concept actually draws the two previously described desirable features together into one unified concept. Initially, the sharpness concept relied upon the fact that the human eye is a very good evaluation tool where it comes to the comparison of micrograph quality.[4] The average human eye may perceive spatial resolution on the order of about 0.2 mm. That being the case, Table 1 summarizes the computed size of a 1 mm feature in a micrograph as a function of magnification, as well as the smallest feature resolvable by the human eye (@ 0.2 mm resolution). This represents the actual resolution performance necessary for the micrograph to appear sharp to the unaided eye. Implied in this evaluation is the proper SEM magnification calibration and that the photographic CRT is properly focused to less than 0.2 mm - which is readily possible.

The data presented in Table 1 can be analyzed in a number of ways. For this discussion, one of the conclusions made in the original AMRAY Technical Bulletin was that for a micrograph to appear perfectly sharp to the eye at 100,000x magnification, the SEM must function at 2 nm resolution or better. In 1977, when that article was first published, 2 nm resolution was generally unattainable in the secondary electron detection mode of most SEMs and so a micrograph at 100,000x always appeared unsharp to the eye and thus contained some "empty" magnification. To obtain an instrument resolution of 7 nm, a micrograph at 28,000x should appear sharp to the eye or at least contain some sharp elements. Similarly at 20,000x the instrument needed to be performing at 10 nm or better resolution. The important feature presented by this Bulletin was that a **trained eye** could be used to evaluate the day to day performance of an SEM without any special procedures. This procedure was also a highly **subjective** approach, based upon an understanding of image sharpness and the training of the operator and thus, a reasonable amount of uncertainty is expected. However, this basic idea provided the basis for this paper because **with advanced computer processing much of the subjectivity can be eliminated.**

Today, contemporary SEMs perform far better than those discussed in the original AMRAY Technical Bulletin[4] and that table can be expanded as needed. One advantage presented by Table 1 is that it is extremely applicable and it also defines the performance levels for the expected sharpness for most low accelerating voltage SEM applications, as well. This means that if an instrument is specified to provide 10 nm resolution at 1.0 kV accelerating voltage it should be capable of providing a sharp micrograph at 20,000x. This goal should be possible for most tungsten filament instruments and all LaB_6 instruments. A sharp 50,000x micrograph at 1.0 kV should be attainable by most post-lens field emission instruments thus implying 4 nm resolution.

The goal of this work was four fold. The first was to attempt to explore the usefulness of the sharpness criteria as a practical means of assessing instrument performance. The second goal was to develop a sample or samples capable of use in the determination of the sharpness of an SEM. The third task was the development of an automated, objective manner to analyze the image and determine the sharpness in a quantitative manner and the final goal was to apply the automated procedure to real-world production samples.

3.0 Materials and Methods

3.1 Scanning Electron Microscope.

The SEM used in this work was either an analog electronics Hitachi S-800[1], digital electronics equipped S-4000S or S-4500 cold field emission instrument.

3.2 Image Analysis System.

The image analysis system used in this study was the NIST developed, personal computer-based ISAAC System described in an earlier paper.[16]

3.3 Samples.

A number of different types of samples were tested for their applicability to the sharpness technique. It was determined that the following characteristics should be present in any sample used for determination of

sharpness. First, the sample must be able to be formed or placed into a semiconductor wafer type configuration. Since the technique is used in automated wafer fabrication instrumentation, the sample must be able to approximate the product being viewed. Second the sample must not be particulate. One of the major problems facing semiconductor processing is particulate contamination. For this technique to be successful, it should not induce any particles, therefore latex spheres or zinc oxide powders were eliminated from the possibilities. Third, the sample cannot introduce contamination to the process. Many semiconductor wafer processing facilities are sensitive to gold. Therefore, samples such as gold-on-carbon were eliminated from the sample possibilities as well.

Two possible samples were found to be useful in the determination of sharpness in laboratory instruments. The first was etched glass, the second was a semiconductor wafer etching processing artifact referred to as "grass."[15] A third "real-world" semiconductor sample of polysilicon was also explored.

Irrespective of the sample chosen, proper application of this method requires that for an "ideal" sample it would have diversified size features with known structure in all directions and dimension ranges, it would be "fractal-like." This type of sample would allow the user to precisely measure the geometric parameters of the primary electron beam. Currently no such sample is available, the only choice is to find or produce artifacts which, at least in the most important magnification ranges, have satisfactory structure. Beyond the geometry requirement, the sample must result in reasonably noiseless images with good contrast at least in the upper magnification range.

3.4 Software

The image processing software generally used through this study is a commercially available scientific image analysis program called IPlab Spectrum [17] which has been modified in collaboration with NIST for sharpness analysis. The Fourier calculations were done within this program using its built-in, fast Fourier transform (FFT) routines with resolution of 1024 elements. The final calculation of the data gained from images and Fourier computation was accomplished using Microsoft Excel (Version 5) spreadsheet software.

4.0 RESULTS

A number of very important image processing techniques are based on Fourier and inverse Fourier (and other frequency space) transforms. For example, image compression or convolution and correlation methods operate in the frequency domain, because these techniques are much faster than many similar operations in the original, spatial domain. The mathematical background of the Fourier transform lies with the theorem which states that it is possible to form any one-dimensional function $f(x)$ as a summation of series of sine and cosine terms of increasing frequency. The real variable, x can represent distance or time in one dimension across an image.

The magnitude function, $F(u)$ is called the Fourier spectrum of $f(x)$, and $f(u)$ is its phase angle. In this study the calculations are limited to the use of the magnitude function. The variable u in the Fourier transform is called the frequency variable. $F(u)$ is composed of an infinite sum of sine and cosine terms and u determines the frequency of its corresponding sine-cosine pair. The Fourier transform can be extended to a function of two x and y (spatial domain) variables. Consequently the mathematical expressions of the two dimensional Fourier

transform pair are similar to the one dimensional one.

Figure 1 demonstrates the analysis of a simple subject. Described is an image of a square (with values of 0 inside the square, 255 elsewhere) that is a two dimensional step function. Figure 1b is its power spectrum. The bottom part, Figure 1c, shows the intensity distribution of the central horizontal line of the power spectrum of Figure 1b. The vertical axis is the magnitude function $F(u)$, while on the horizontal axis the parameter is frequency. Note that the distribution is symmetrical.

In practice, the various software programs utilize discrete Fourier transforms. A digital image is an array of two dimensional samples of the continuous x and y function of the video signal that carries the information about the sample and the primary electron beam (and the video signal electronics). The mathematical expressions for discrete functions are described in the literature.[9]

Figure 2 shows the effect of focus on the Fourier transform. Figure 2a is a micrograph of the secondary electron image of platinum evaporated on a gold-on-carbon sample (magnification = 100 000x). The focus is shifted first slightly out-of-focus in Figure 2b and then substantially out-of-focus in Figure 2c. The images were taken on the same sample with different final lens settings. The power spectra are shown in Figures 2d, e and f, respectively. Note that the lighter center spot decreases as the original image is less focused due to the diminishing high frequency information. There is sufficient sensitivity in the sharpness technique to detect small changes in final lens voltage (i.e., focus) changes.

In a scanning electron micrograph, the high frequency information increases as the image gets sharper and the center part of the power spectra gets broader, as it can be seen from Figure 2. This can be used in calculations to compute relative sharpness of an image series. In IPlab Spectrum, with the use of a script containing the FFT routine, the frequency domain representation of a total of 32 vertical (y) lines was computed. Then the image was turned 90 degrees to calculate the originally horizontal (x) values with the same method. In order to obtain lower noise level, the results of the 32 individual calculations were added together. With this sampling algorithm, the calculations occurred on the central two third of the images in order to minimize the effect of any possible distortions of the original image. The x and y sums were saved as text files.

Further calculations were accomplished with Excel software. Since the Fourier spectrum as a function of increasing frequency on the line scans chosen from SEM images decreases rather rapidly, it is sufficient to choose only a part of the frequency domain for the further calculations. The part chosen is the 200 values next to the central, zero frequency. This central value carries the brightness information, which is not important for this analysis. The values were added together. The result is directly proportional to the high frequency components of the image.

Figure 3 shows the distribution of the result of FFT calculations on a sequence of micrographs. The distribution in Figure 3 was obtained through FFT calculations taken with objective lens current values resulting in under-focused, focused, and then over-focused images. The distributions for x and y directions are alike if no astigmatism is present and the noise conditions in the micrographs are equal.

This technique can also be utilized to detect astigmatism in the image. Figure 4 shows an astigmatic secondary

electron image (a); its power spectrum (b) shows line profiles of an astigmatic image. The horizontal line profile (x) shows less gradual drop-off at higher frequencies than the vertical one (y). The dissimilarity of the center parts is due to the difference in diameter of the astigmatic primary electron beam in x and y directions. Analysis of the image from multiple directions permits the reconstruction of the primary electron beam shape and with calibration, the beam diameter could be determined.

5.0 CONCLUSION

The technique described here utilizing the sharpness concept is facilitated by the use of the Fourier techniques to analyze the electron micrograph to obtain the evaluation. This is not the first application of Fourier techniques to SEM images[8,13] (Dodson and Joy, 1990, Martin et al., 1995) but it is the first integrated approach considering the sample, computer analysis and measurement algorithm. This technique can be used to check and optimize two basic parameters of the primary electron beam, the focus and the astigmatism. It facilitates the periodic resolution determination of the SEM in an objective and quantitative form. The few minutes required to use this method allows the user to perform it even every day (or on the production line several times a day). To be able to get objective, quantitative data about the resolution of the SEM can be important, especially where high resolution imaging or accurate linewidth metrology is a concern. If these calculations are carried out on dedicated, specialized hardware (and/or software) the speed can be substantially higher. For example, the Pentacle[14] system is based upon a Pentium PC system with fast, TV frequency frame grabber and dedicated software. The system is claimed to be capable of performing 8 FFT images per second. Although this system was developed for use on transmission electron microscopes, it clearly demonstrates the possibility of faster, relatively inexpensive hardware set-ups suitable for practical applications. Therefore, the total integration of this procedure is possible in future automated inspection instrumentation.

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7.0 REFERENCES

1. Contribution of the National Institute of Standards and Technology (NIST). This work was supported in part by the National Semiconductor Metrology Program at NIST; not subject to copyright.

2. Certain commercial equipment is identified in this report in order to describe the experimental procedure adequately. Such Identification does not imply recommendation or endorsement by NIST, nor does it imply that the equipment identified is necessarily the best available for the purpose.

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Table 1
Image Feature Size vs. Micrograph Magnification**

Magnification	True size of 1 mm Feature	True size of 0.2 mm Feature
100,000x	10 nm	2 nm
50,000x	20 nm	4 nm
28,570x	35 nm	7 nm
20,000x	50 nm	10 nm
10,000x	100 nm	20 nm
5,000x	200 nm	40 nm
2,000x	500 nm	100 nm
1,000x	1000 nm (1 μm)	200 nm
500x	2000 nm (2 μm)	400 nm
200x	5000 nm (5 μm)	1000 nm (1 μm)

** Proper instrument calibration to a NIST traceable magnification standard is assumed.

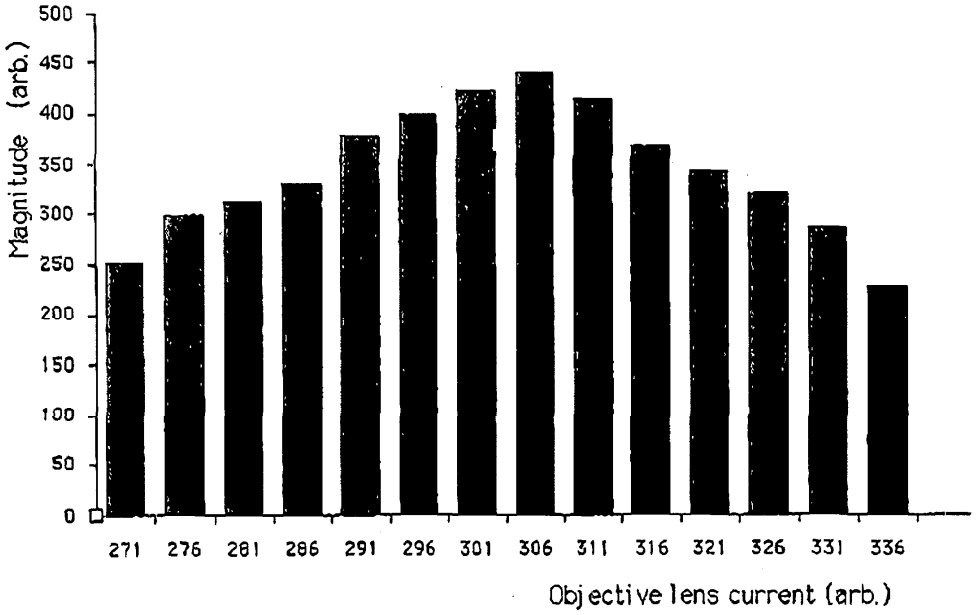

Figure 3. Distribution of the result of FFT calculations on a through focus series of micrographs as described in the text.

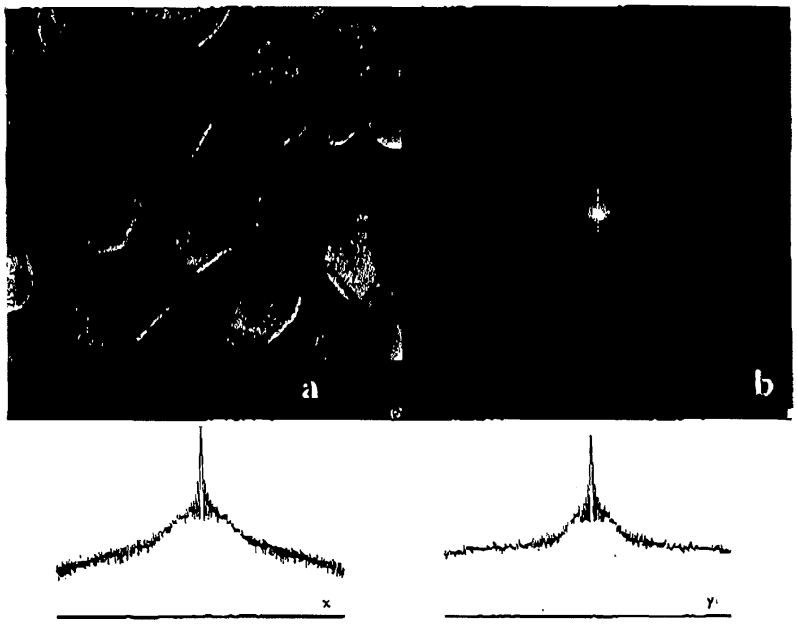

Figure 4. Secondary electron image, a, and its Fourier Transform, b, revealing the presence of astigmatism in the image.